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Progress in Development of Nanostructured Gradient Index Optical Fibers and Micro-Optical Components

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ABSTRACT

Nanostructured gradient index (nGRIN) elements are a new class of planar-surface micro-optical elements. An effective gradient index profile with any arbitrary refractive index distribution can be developed with internal discrete nanostructure composed of two types of glasses. A low-cost modified stack-and-draw technology commonly used for photonic crystal fibres development is used for development of nGRIN components and fibers. The effective medium Maxwell-Garnett theory is applied to describe performance of the components. We report on recent progress in development of nanostructured core fibres and a wide range of nGRIN micro-optical components as microlenses, axicons, vortices and diffractive optical elements.

Keywords: nanotechnology, optical fibers, microoptics, gradient index optics.

1. INTRODUCTION

The gradient index (GRIN) optical components are attractive due to their potential applications in imaging systems, fiber optics, laser collimation, and optical couplers [1]. For those applications, there is a need for small-diameter, easily integrable micro-optical components. Gradient refractive index (GRIN) materials are among the best solutions to achieve this. GRIN materials exhibit inhomogeneous surface refraction and continuous bulk focusing.

The concept of nanostructured optics is based on the Effective Medium Approximation (EMA), in which a nanostructured optical element is constructed of discrete sub-wavelength sized glass rods made of two, or more, different glasses [2]. The boundary condition for the use of the EMA is defined as the diameter of the individual rods being below $\lambda/(2\pi)$ of the wavelength of the propagating light. When this boundary condition is fulfilled the whole structure acts like a continuous medium with an effective refractive index distribution equal to the spatially averaged index of the rods. The effective optical properties of the optical elements depend on the precise pattern of the rods in the structure as well as the refractive indices of the rods. The process of the design of a nanostructured optical element begins with the determination of the desired refractive index distribution, which will be the target function for the design of the glass nanostructure distribution. We have already demonstrated the practical use of this method by fabricating parabolic GRIN microlenses, elliptical GRIN microlenses, axicon GRIN microlenses, diffractive optical elements (DOE), birefringent artificial glass materials as well as fibers with nanostructured parabolic refractive index profile cores [3-5].

2. DESIGN OF ACHROMATIC GRIN MICROLENSES

The nanostructured microlenses described in this paper are based on a structure consisting of glass nanorods of the diameter of about 200 nm with two distinct refractive indices, as shown in Fig. 1a. In case of nGRIN lenses fabricated in scope of this work, the glasses used for the nanorods were in-house developed glasses NC34 (n_0 = 1.5432 at λ = 1550 nm) and NC21A (n_1 = 1.5101 at λ = 1550 nm), which are both borosilicate glasses and have been used previously in drawing of nanostructured core GRIN fibres. The nanostructure has been designed so the effective refractive index would change parabolically between these two values, from the optical axis to the edge of the aperture, which can be seen in Fig. 1b. Thus, a good quality gradient index microlens has been formed. The aperture size of the lens is limited to about d = 20 µm, due to the two main factors. First is the limit on the number of elements in the nanostructure, which results from manual assembly process of the nanostructure preform and is imposed by the size of the furnaces used in the fabrication process. The second condition is the boundary condition of the EMA that determine a maximum size of nanorod with respect to operating wavelength. According to EMA theory a size of single nanorods should be much smaller than wavelength, however in practice a size of single nanorods should be smaller than $\lambda/4$ [4,5]. Keeping that, and glasses used in structure fabrication, as a constant, the desired effective focal length (EFL) of the lens can be achieved by the choice of the optical element length. The longer the EFL desired, the thinner should be the lens.

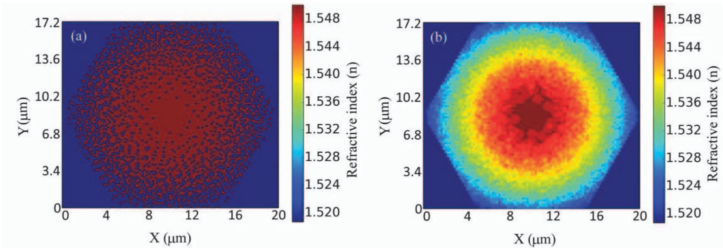

Figure 1: (a) Internal nanostructure of the GRIN microlens; (b) Calculated effective refractive index distribution in a nanostructured GRIN microlens.

The index of refraction of an optical glass changes as a function of the wavelength of the incident light. This means that different wavelengths of light are bent differently by the same glass lens due to angular dispersion. When different wavelengths of light are focused at different points along the optical axis, it is called an axial chromatic aberration. A traditional achromatic lens typically consists of two glass elements connected together to correct or to minimize the chromatic aberration inherent to singlet lenses. Such achromatic doublet utilizes a higher dispersion negative element to balance the lower dispersive positive element. By balancing the optical power of that element with respect to its glass dispersion, one can have a common focus for the chosen incident wavelength range.

In the case of the GRIN lenses, chromatic aberration results mainly from the changes of the index profile. The GRIN lens has, in its most basic form, a refractive index which changes parabolically with distance from the optical axis, i.e. it has the form:

$$n = n_0\left(1 - \frac{A}{2}r^2\right) \tag{1}$$

where n_0 is the on-axis refractive index, r – the distance from the optical axis, and A is a refractive index gradient constant.

The nGRIN lens, which utilises the EMA approach, acquires its profile by mixing glass rods made from two distinctive glasses in different ratios from the centre of the lens towards its edges. Refractive indices of each glass change with the incident wavelength. Depending on the glasses used, this can in turn change both refractive indices by the same amount, or change their ratio n_0/n_1. This ratio is the most important factor affecting the chromatic aberration of the lens, as it is directly connected with the refractive gradient index constant A. This results in change of the lens refractive index profile, as shown in Fig. 2b. If both glasses have refractive indices changed by the same mount, the shape of the refractive index profile remains constant, which has weak influence on the chromatic aberration, as can be seen in Fig. 2a. When this is coupled with a change of both indices, it can result in a single achromatic lens.

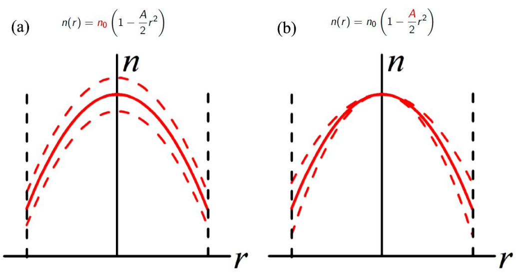

Figure 2: (a) Change of the refractive index for both glasses simultaneously; (b) Change of the refractive index resulting in change of the refractive index ratio n_0/n_1.

The NC21A and NC34 glasses used for the development of the nGRIN lenses are modifications of the same borosilicate base glass. NC21 glass consists of 56.83% SiO_2, 3.63% K_2O, 9.52% Na_2O, 6.23% Li_2O, 23.19% B_2O_3 and 0.61% Al_2O_3. NC34 glass is modified mainly by adding 9% BaO and reduced of content of SiO_2 and K_2O [6]. The NC21/NC34 pair of glasses has an expansion coefficient difference $\Delta\alpha = 0.4\times10^{-7}\,K^{-1}$, which is sufficiently small for joint thermal processing. During the drawing at the fiber drawing tower the glasses are kept at a temperature between the curvature and sphere points. For NC21/NC34 the difference in the curvature temperature is $\Delta T_c = 50$ °C and difference in sphere temperature is $\Delta T_{kph} = 35$ °C. The measured transmission for both glasses is very similar and cover the range between 480 nm and 2100 nm.

Material dispersion characteristics of glasses are very similar. The wavelength dependence of their refractive indices – Fig. 3a – is almost identical between 800 nm and 1600 nm, with the refractive index difference varying by less than 0.001 for this range. As a result the calculated pitch length of the nGRIN lens varies non-monotonically from $P = 298$ µm at $\lambda = 800$ nm down to $P = 297$ µm at $\lambda = 1600$ nm with a maximum of P = 299 µm at $\lambda = 970$ nm. For the nGRIN lenses cut to the length of 52 µm the variation of the effective focal length (EFL) – Fig. 3b – is by an order of magnitude below the uncertainty error given by the measurement accuracy of the glasses' refractive indices. Hence the lens shows achromatic behavior.

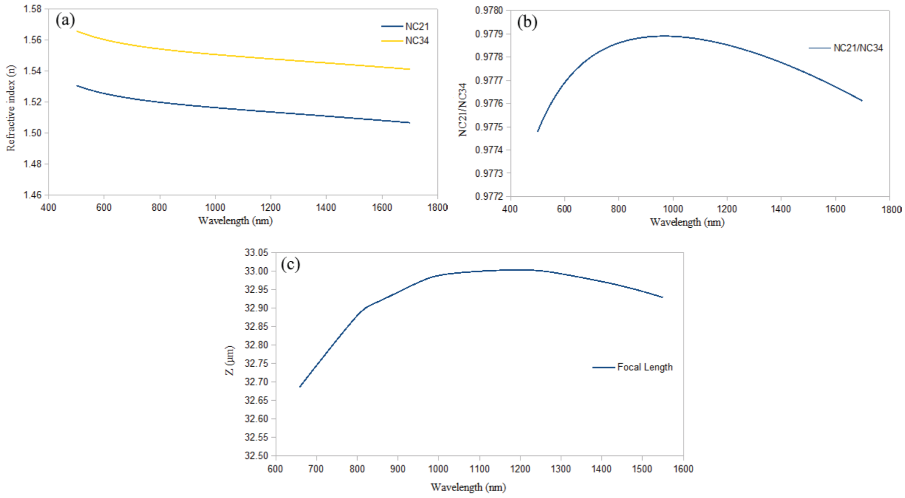

Figure 3: (a, b) Refractive indices of NC21A and NC34 glasses; (c) Calculated effective focal length for the nGRIN lens with a length of 52 µm.

3. DEVELOPMENT OF NANOASTRUCTURED GRIN MICROLENSES

The fabrication procedure of the nanostructured optical elements has been extensively described in our previous works [7]. The first step is the assembly of the preform consisting of the glass rods made of two different glasses. The hexagonal shape of preform ensures that rods remain in the same positions relative to each other. The designed structure is shown in Fig. 1. During the second step, the preform is drawn at a fiber drawing tower, with the end result being an optical fibre 125 µm in diameter, with the nanostructure positioned at the center and having 20 µm at the diagonal. The structure consists of 100 rods across the diagonal. Size of a single glass rod is about 200 nm. This means that the EMA boundary condition $\lambda/2\times\pi$ is fulfilled for $\lambda > 1000$ nm. We are assuming that the diffusion between glasses in the structure will further lower down the wavelength of the incident light for which the lens is still effectively a continuous medium. The quality of the fabricated structure has been verified using Scanning Electron Microscopy (SEM). Corresponding images are shown in Fig. 3a. In the third step the fiber is cut with a diamond saw and polished into the final lens samples with thicknesses of 52 µm. In the last step, these lenses were integrated with single mode optical fibers (SMF). A glass spacer with a thickness of 93 µm and a diameter of 125 µm is attached to the end of the optical fiber with mode diameter of 9 µm (at $1/e^2$ of the maximum intensity) measured at $\lambda = 1550$ nm. Nanostructured lens is then attached to the end of this spacer, which is shown in Fig. 3b. The spacer ensures that the lens works at its full aperture. Full explanation of the integration process is presented in [8].

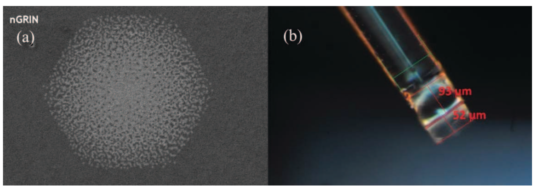

Figure 4: (a) SEM image of the fabricated lens structure; (b) Optical element attached to the SEM fiber.

4. CHARACTERIZATION OF NANOASTRUCTURED GRIN MICROLENSES

Direct measurement of gradient index distribution in the developed GRIN lenses is not possible since those elements are too small for typical methods used to measure refractive index distribution or phase contrast [9]. Therefore we have measured the effective parameters of lenses to verify refractive index distribution in the lens using the imaging setup shown in Fig. 5. The fiber with the integrated lens was clamped to a high precision translation stage. The fiber was then coupled with the continuous-wave laser sources emitting at $\lambda = 1550$ nm, 1310 nm and 850 nm. The beam formed by the nanostructured lens was focused by a 40× microscope lens onto a CCD camera. For each laser source, different camera had to be used. The distance between the CCD surface and the microscope was chosen in each measurement as such to keep the size of the structure image on the CCD camera constant. The plane of focus of the setup was constant with respect to the objective. The images of the beam cross-sections could be focused on the CCD continuously from the lens facet by the translation of the fiber with the structured lens, as shown in Fig. 5. The spatial resolution of each transversal image was determined by imaging the microscope calibration target with the same system at the same magnification. The maximum intensity of the focused beam is observed at the distance of 10 μm for 1550 nm and 12 μm for wavelengths 850 and 1310 nm. FWHM measurement for the same lens shows focal plane at 10 μm (FWHM below 4 μm) for all wavelengths. Because of the 2 μm accuracy of lens positioning, those measurements are consistent. Based on those measurements effective focal lengths of the lens are calculated to be 28 μm, 30 μm, and 21 μm for the 850, 1310, and 1550 nm wavelengths.

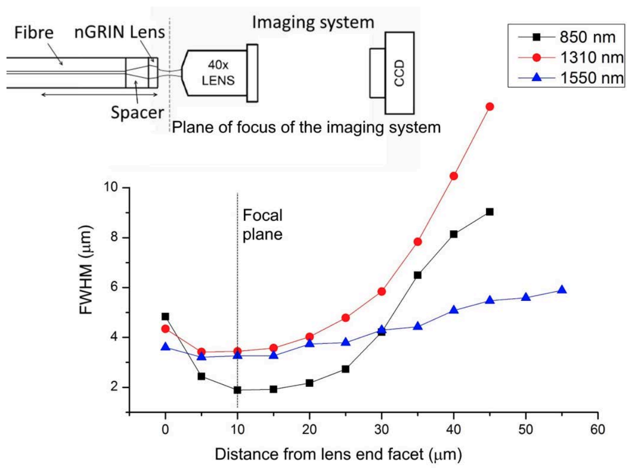

Figure 5: (a) Schematic of the lens imagining setup; (b) Propagating beam FWHM for 850, 1310, and 1550 nm.

5. CONCLUSIONS

We have demonstrated the design and fabrication of a nanostructured GRIN lens which is completely flat-parallel, allowing for an easy integration with standard optical fibers. The method allow to develop various micro-optical components based on the same approach as arbitrary 2D refractive index distribution. This way refractive and diffractive beam profiles, as well as their polarization and wavelength-depended properties can be engineered.

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